# (MAD)*DAM
# Moist Atmosphere Dynamics Data Assimilation Model: Application to 4D-Var Wind Tracing

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# Contents

# Introduction

- Simplified models **allow to**:
  - Develop and implement new algorithms faster than in the NWP case
  - Perform numerical experiments in a controlled environment in which various issues, difficult to grasp in a real NWP, can more easily be understood

- Simplified models **should be**:
  - complex enough to capture main physical aspects of the phenomena of interest in order to explain the observed features of atmospheric circulation and thus to be of any value for NWP

# Introduction

- The new intermediate-complexity system (MADDAM) was developed to study:
  - Interaction of gravity waves and moisture in 4D-Var
  - Coupling of the aerosols-moisture-winds in 4D-Var (wind tracing)

- Two components of the system:
  - Moist Atmosphere Dynamics (MAD) forecast model
  - Moist Atmosphere Dynamics Data Assimilation Model (MADDAM)

# MAD forecast model

- Single-vertical level spectral prognostic model for the Tropics (based on Gill (1980,1982), Davey and Gill (1987), built upon Žagar (2008,2012)
- Simulates **nonlinear** interactions between condensational heating and dynamics
- Prescribed baroclinic (vertical wavenumber m=1) vertical structure with sinusoidal profile of of heating:

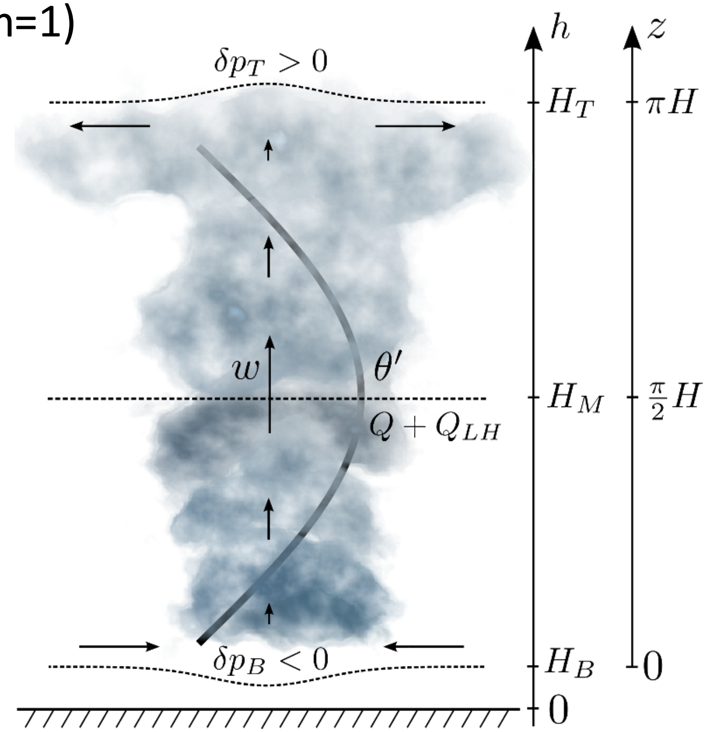
$$Q_{LH} = \tilde{Q}_{LH}(x,y,t)\sin\left(\frac{z}{H}\right)\frac{\theta_0(z)}{\theta_{00}}$$

$$\theta' = \widetilde{\theta}'(x,y,t)\sin\left(\frac{z}{H}\right)\frac{\theta_0(z)}{\theta_{00}}$$

$$w = \widetilde{w}(x,y,t)\sin\left(\frac{z}{H}\right)$$

$$\mathbf{v}_h = \tilde{\mathbf{v}}_h(x,y,t)\cos\left(\frac{z}{H}\right)$$

$$p' = \widetilde{p}'\cos\left(\frac{z}{H}\right)\frac{\rho_0(z)}{\rho_{00}}$$




Zaplotnik, Žagar, Gustafsson (QJRMS, 2018)

# MAD forecast model

**Prognostic equations**

$$\frac{\partial \theta}{\partial t} + (\mathbf{v} \cdot \nabla)\theta - \frac{\theta_{00} N^2 H}{g}(\nabla \cdot \mathbf{v}) = \frac{L_c}{2\, c_p} C + \mathrm{Q} - \varepsilon_\theta \theta$$

Potential temp. pert. at midtropospheric level (~400 hPa)
Thermodynamic + continuity eq.

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + f\mathbf{k}\times\mathbf{v} = \frac{gH}{\theta_{00}} \nabla\theta - \varepsilon_{\mathbf{v}}\mathbf{v}$$

Winds at lower level (~700 hPa)

$$\frac{\partial q}{\partial t} + \nabla \cdot (\mathbf{v}\, q) = E - C$$

Specific humidity [g/kg] at lower level

$$C = -\nabla \cdot (\mathbf{v}\, q) \;\; \text{if} \;\; q \geq q_s(\theta)$$

Condensation due to large-scale convergence
Excess humidity is immediately released

$$q_s(\theta) = \frac{e_s\big(T(\theta)\big)}{p} \frac{R_d}{R_v}$$

Temperature-dependent saturation specific humidity

$$\frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{v}\, c) = -K_w c P - K_d c + S^+ - S^-$$

Total aerosol mass mixing ratio [$\mu$g/kg] at lower level

# MAD forecast model

## Model parameters

- Tropopause height: $\pi H$ = 15 km
- Lapse rate: $d\theta_0/dz$ = 4 K km$^{-1}$
- Mid-level mean potential temperature: $\theta_{00}$ = 333 K
- Bouyancy frequency: $N$= 0.011 s$^{-1}$, horizontal phase speed: $c = NH$ = 50 m/s
- Deformation radius: $R_e = \sqrt{c/(2\beta)}$ = 1000 km, adjustment time scale: $T = R_e/c$ = 6 h

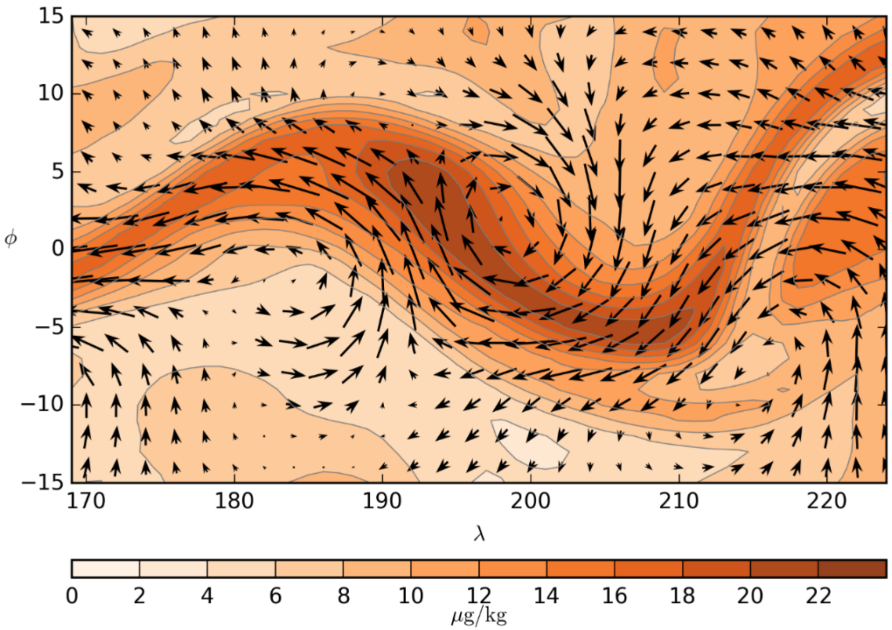
## Numerical formulation

- Spectral model, $N_k$=119, $N_l$=23, a total of 2215 2D Fourier waves after elliptic truncation, quadratic grid, 4th order implicit numerical diffusion
- Leap-frog time-stepping, $\Delta t$=180 s, Asselin filtering
- Domain: tropical belt spanning from 32°S to 32°N, resolution 1°x1°
- Boundary relaxation zone 6° wide, extension zone 7° wide
- Mass fixers to correct negative values due to spectral truncation for positive definite fields, e.g. aerosol, humidity

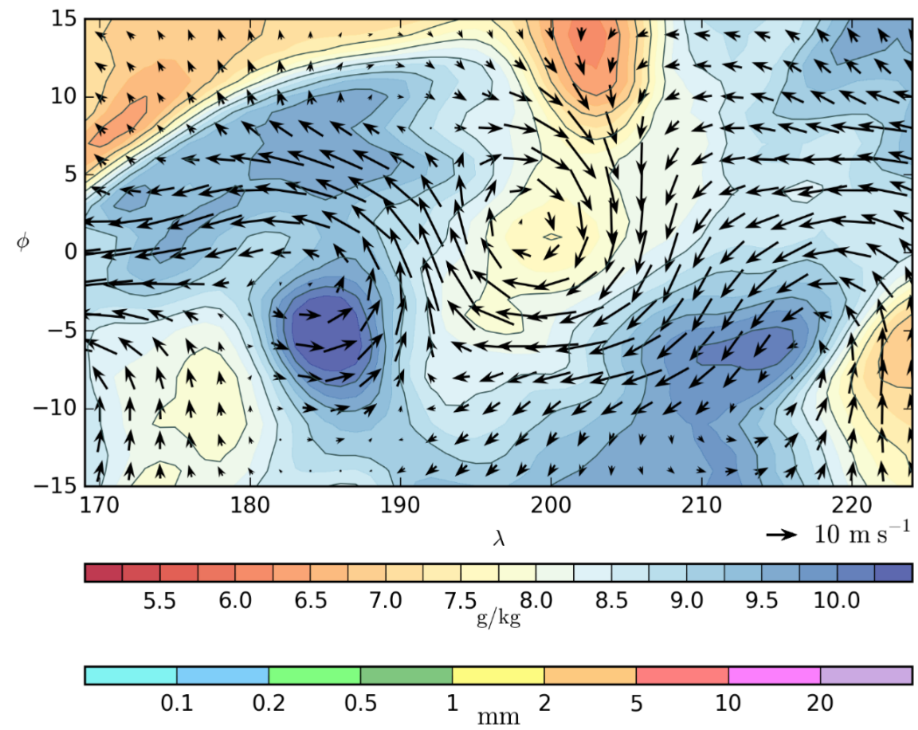
# Aerosol-moisture-wind coupling in forecast model

00

Total aerosol mass mixing ratio



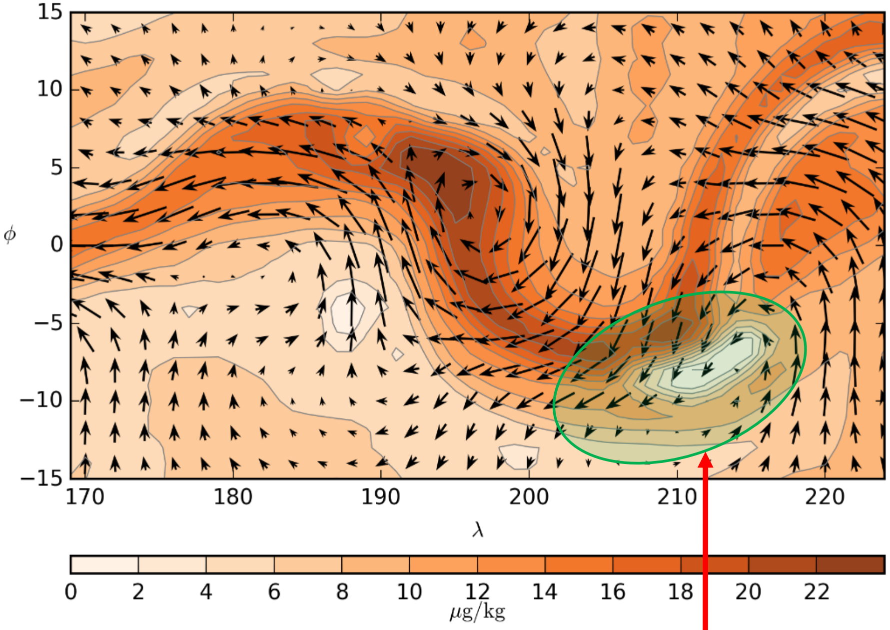

Specific humidity, 6-hour cum. precipitation



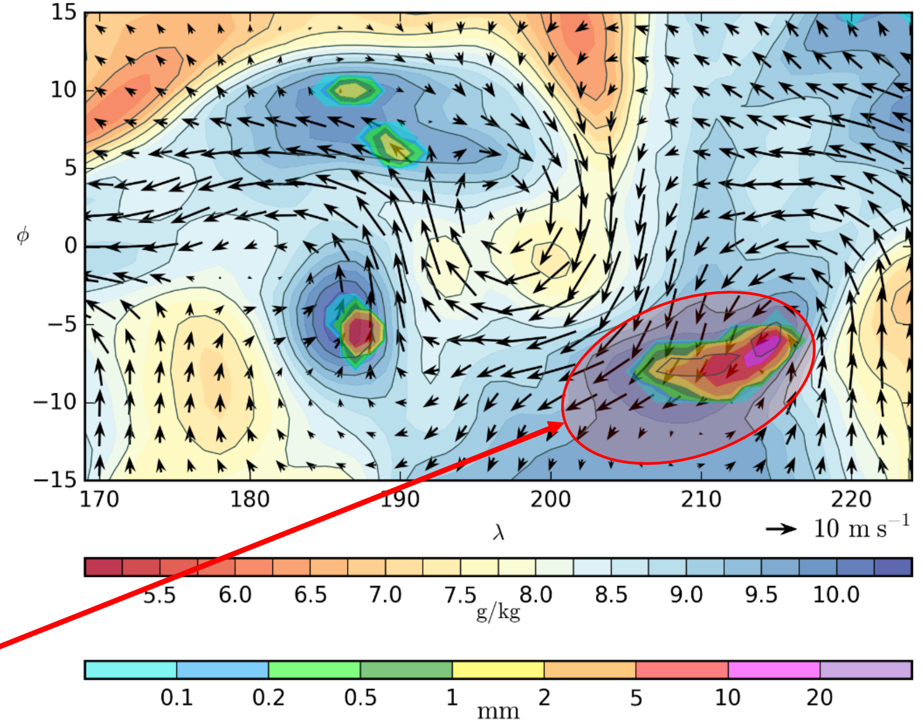
# Aerosol-moisture-wind coupling in forecast model

+06 h

Total aerosol mass mixing ratio




Specific humidity, 6-hour cum. precipitation



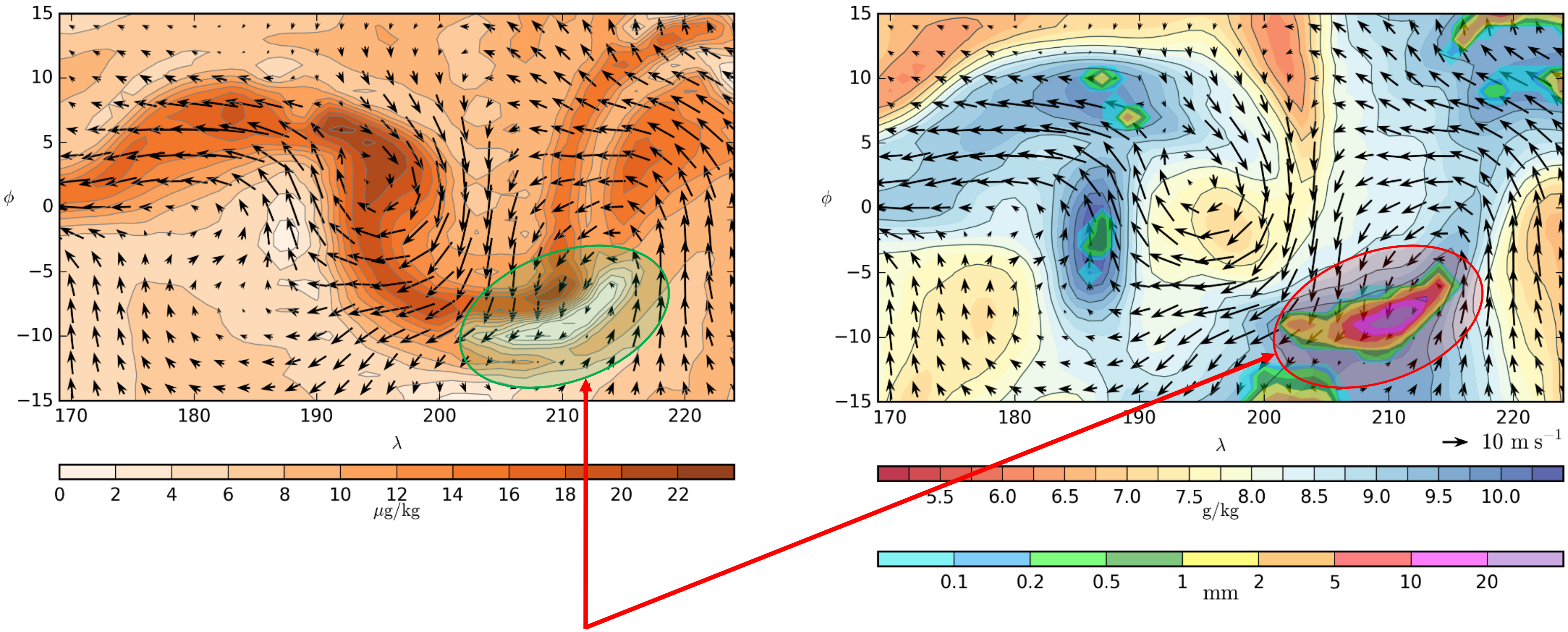

Wet deposition of aerosol

# Aerosol-moisture-wind coupling in forecast model

+12 h

Total aerosol mass mixing ratio

Specific humidity, 6-hour cum. precipitation

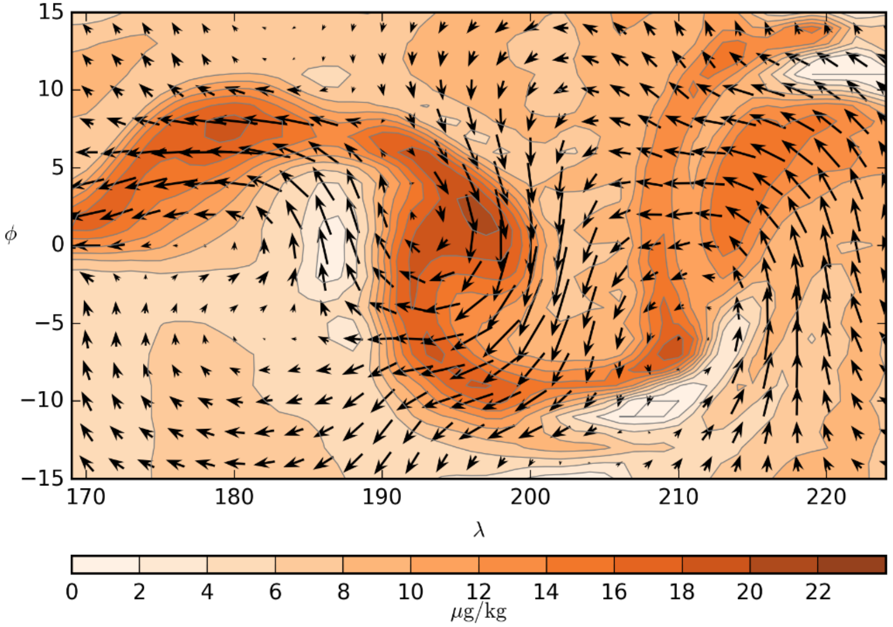



Wet deposition of aerosol

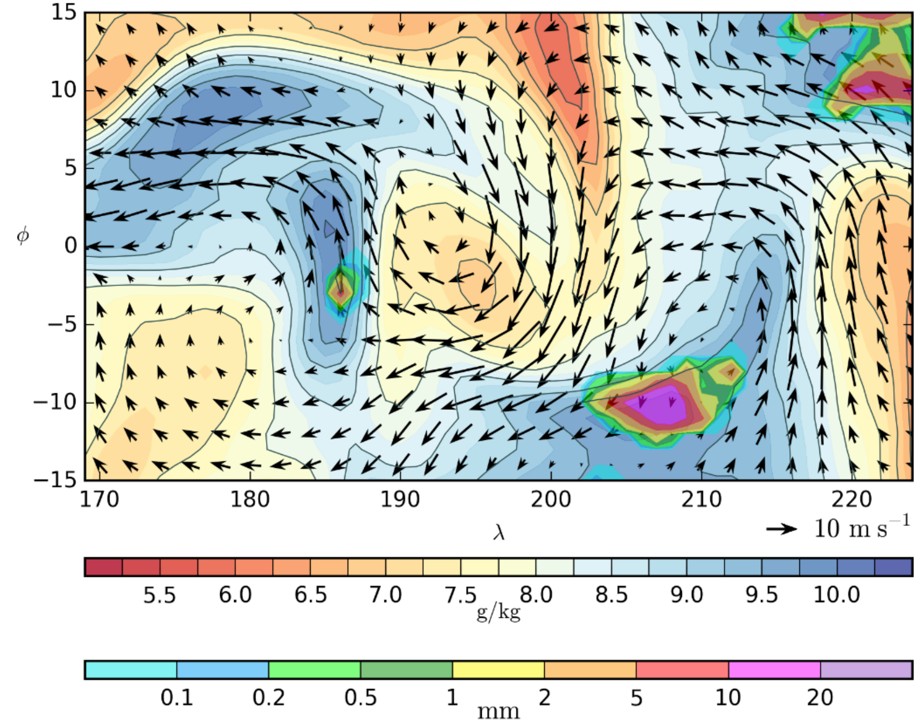
# Aerosol-moisture-wind coupling in forecast model

+18 h

Total aerosol mass mixing ratio



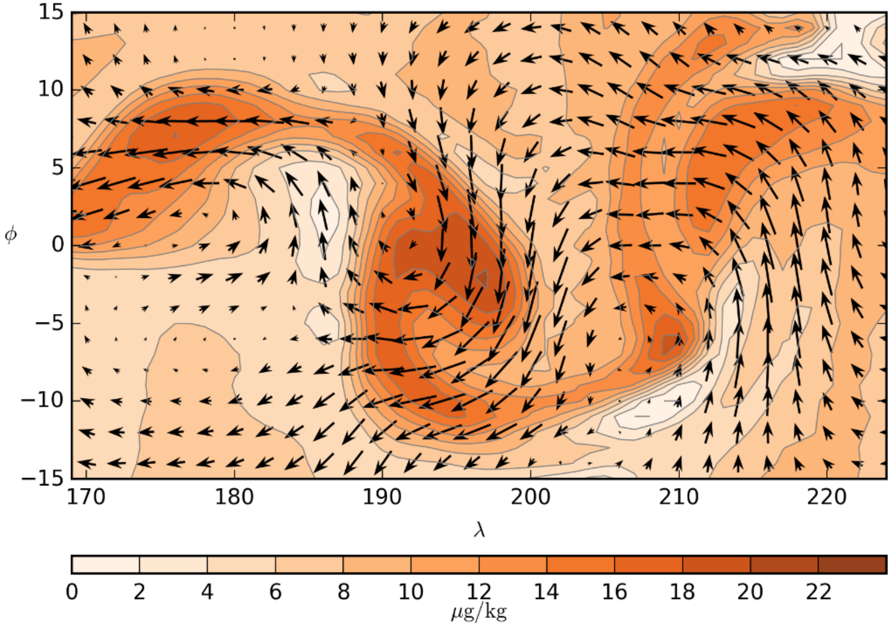

Specific humidity, 6-hour cum. precipitation



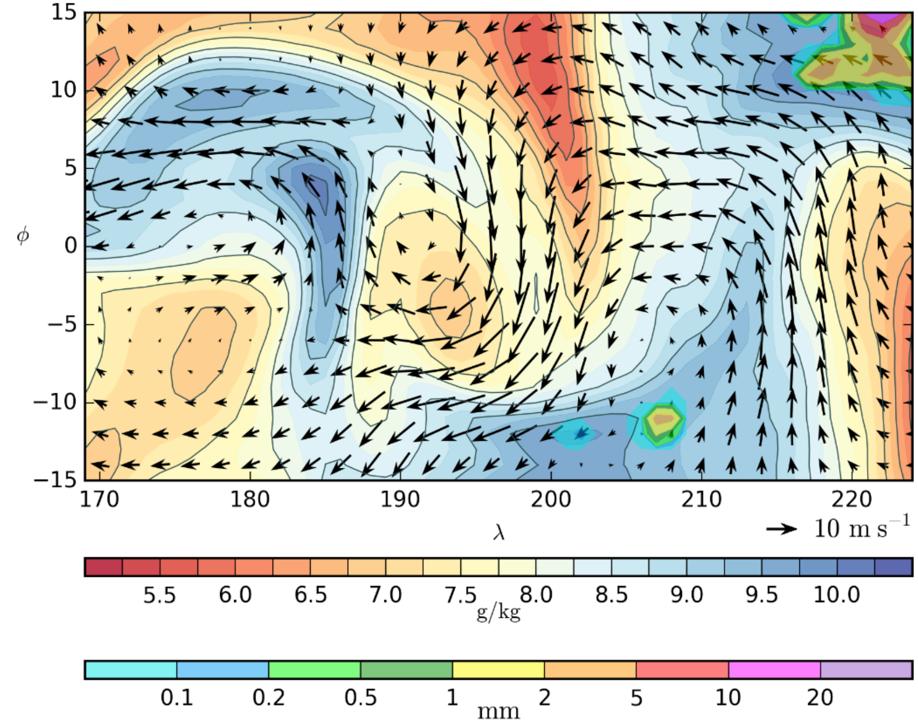
# Aerosol-moisture-wind coupling in forecast model

+24 h

Total aerosol mass mixing ratio



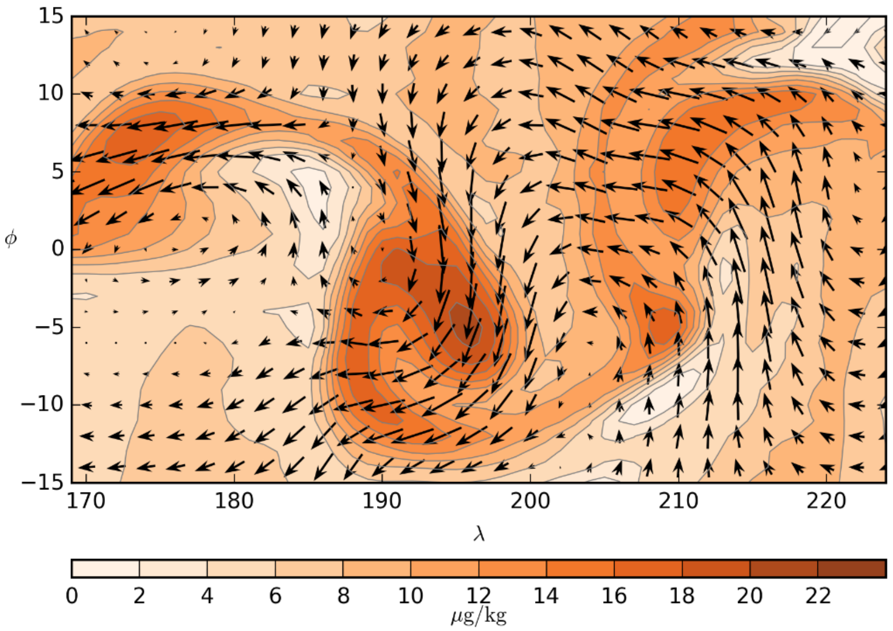

Specific humidity, 6-hour cum. precipitation



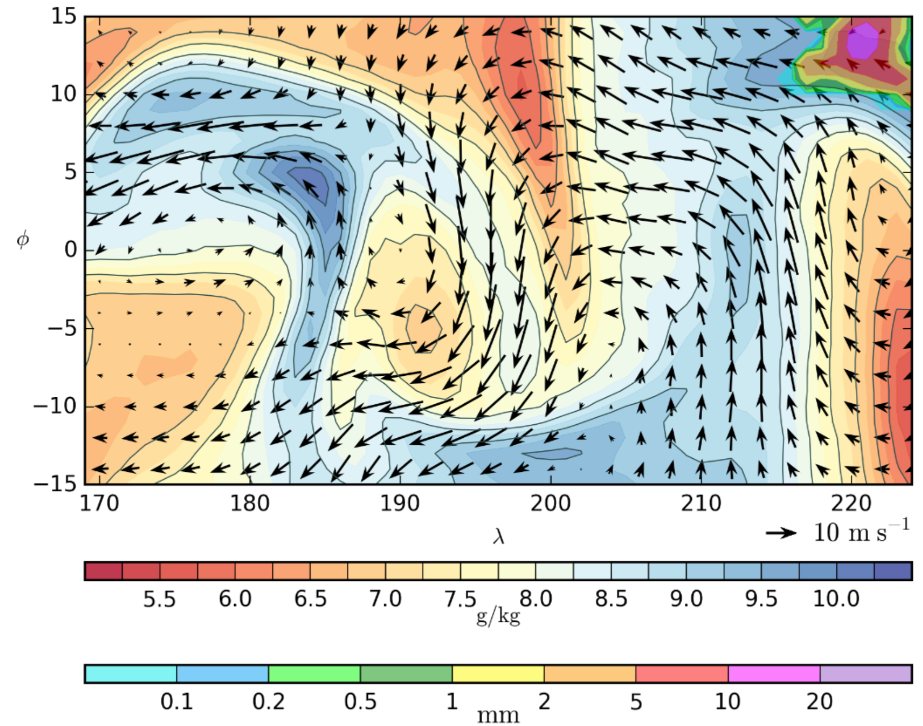
# Aerosol-moisture-wind coupling in forecast model

+30 h

Total aerosol mass mixing ratio



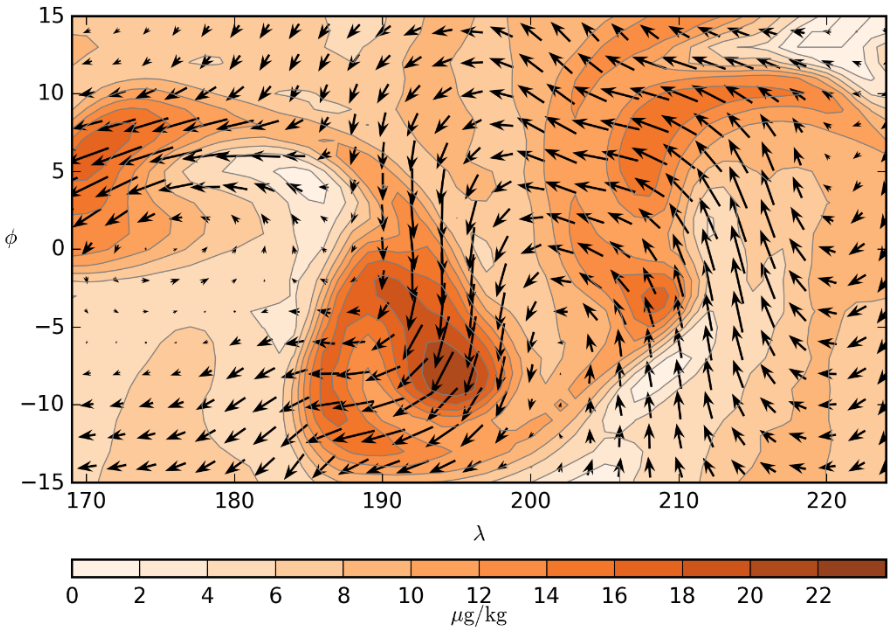

Specific humidity, 6-hour cum. precipitation



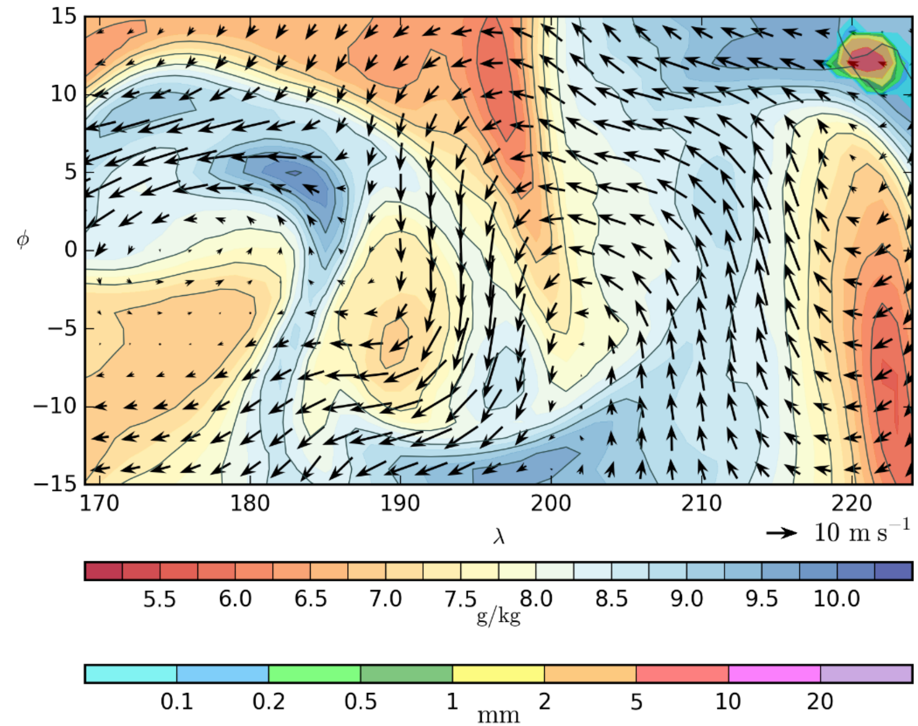
# Aerosol-moisture-wind coupling in forecast model

+36 h

Total aerosol mass mixing ratio



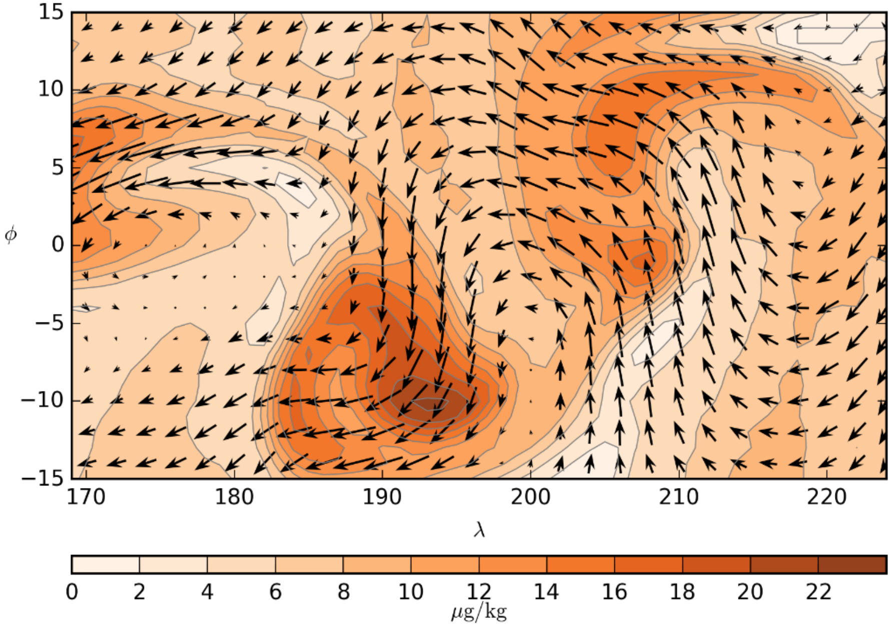

Specific humidity, 6-hour cum. precipitation



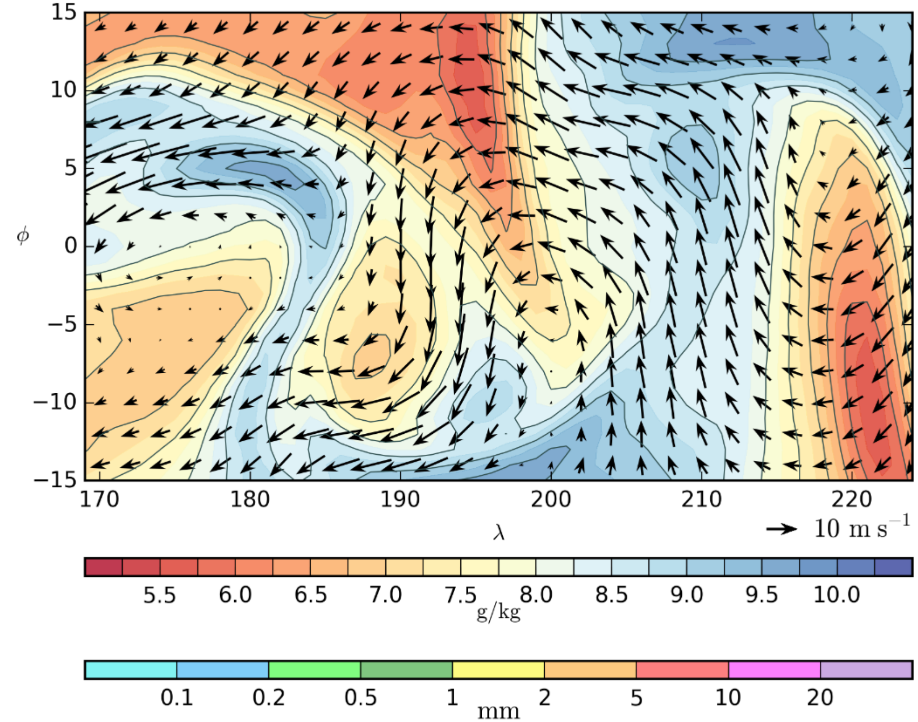
# Aerosol-moisture-wind coupling in forecast model

+42 h

Total aerosol mass mixing ratio



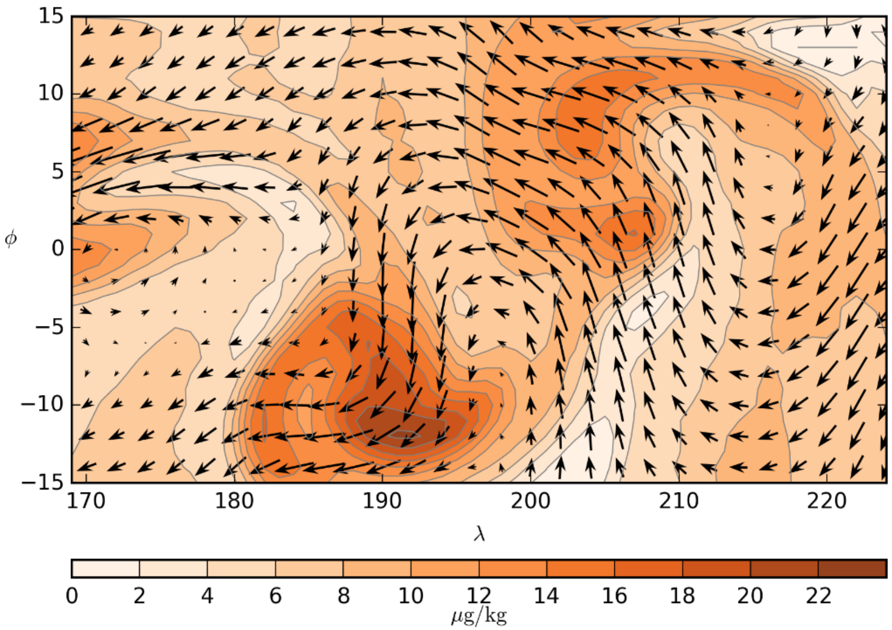

Specific humidity, 6-hour cum. precipitation



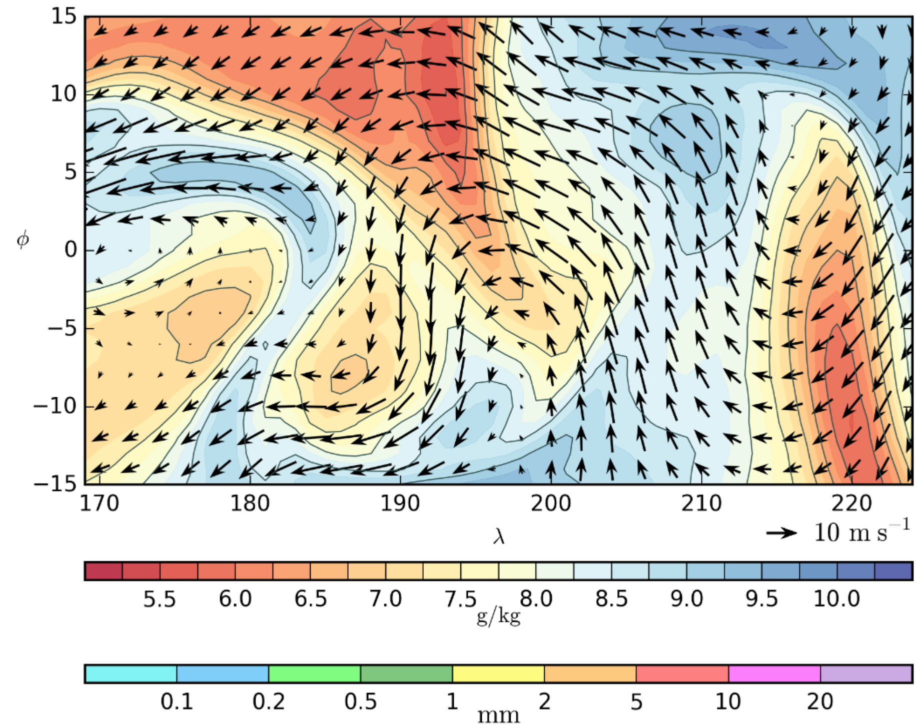
# Aerosol-moisture-wind coupling in forecast model

+48 h

Total aerosol mass mixing ratio




Specific humidity, 6-hour cum. precipitation



# Assimilation model (MADDAM)

**Incremental 4D-Var data assimilation:**

$$J(\boldsymbol{\chi}) = \frac{1}{2}\left(\boldsymbol{\chi} + \boldsymbol{\chi}_g\right)^{\mathrm{T}}\left(\boldsymbol{\chi} + \boldsymbol{\chi}_g\right) + \frac{1}{2}\sum_{k=0}^{N}\left(\mathbf{d}_k - \mathbf{H}_k\mathbf{M}_{t_0\to t_k}\mathbf{L}\boldsymbol{\chi}\right)^{\mathrm{T}}\mathbf{R}_k^{-1}\left(\mathbf{d}_k - \mathbf{H}_k\mathbf{M}_{t_0\to t_k}\mathbf{L}\boldsymbol{\chi}\right)$$

$\boldsymbol{\chi} = [\chi^d, \chi^q, \chi^c]$ .... Control vector (three subvectors)

$\mathbf{L}$, such that $\mathbf{L}^T\mathbf{B}^{-1}\mathbf{L} = \mathbf{I}$ .... Control variable transform

$\mathbf{d}_k = \mathbf{y}_k - H_k M_{t_0\to t_k}\left(\mathbf{x}_g\right)$ .... Innovation vector

$\mathbf{x} - \mathbf{x}_g = \delta\mathbf{x} = \mathbf{L}\boldsymbol{\chi}$ .... Model state increment

$\mathbf{x}_g - \mathbf{x}_b = \delta\mathbf{x}_g = \mathbf{L}\boldsymbol{\chi}_g$ .... Guess increment

# Assimilation model (MADDAM)

**Background-error covariance model for dynamics:**

- Multivariate balanced analysis of $u, v, \theta$ via equatorial linear waves following Žagar et al. (2004, 2008)

$$\begin{bmatrix} \theta(x,y) \\ u(x,y) \\ v(x,y) \end{bmatrix} = \sum_{k=-N_k}^{N_k} \sum_{n=0}^{N_n} \sum_{m=-1}^{1} \chi_{knm}^{d} \begin{bmatrix} \theta_{knm}(y) \\ u_{knm}(y) \\ v_{knm}(y) \end{bmatrix} e^{ikx}$$

- Each horizontal structure function a pruduct of Fourier mode and parabolic cylinder function $D_n$:

$$v_{knm}(x,y) = D_n\left(\frac{y\sqrt{2}}{L_e}\right) = 2^{-\frac{n}{2}} \exp\left(-\frac{y^2}{2\,L_e^2}\right) H_n\left(\frac{y}{L_e}\right)$$

$L_e = \sqrt{c/\beta}$ is equatorial radius of deformation, $H_n$ is Hermite polynomial

- Spectral background-error variance for each mode is estimated from ECMWF EDA (Isaksen, 2010) using Normal modes decomposition software MODES (Žagar, 2015)

# Assimilation model (MADDAM)

**Background-error covariance model for moisture:**

- Control variable = normalized relative humidity (similar to Holm (2002) and Gustafsson (2011))

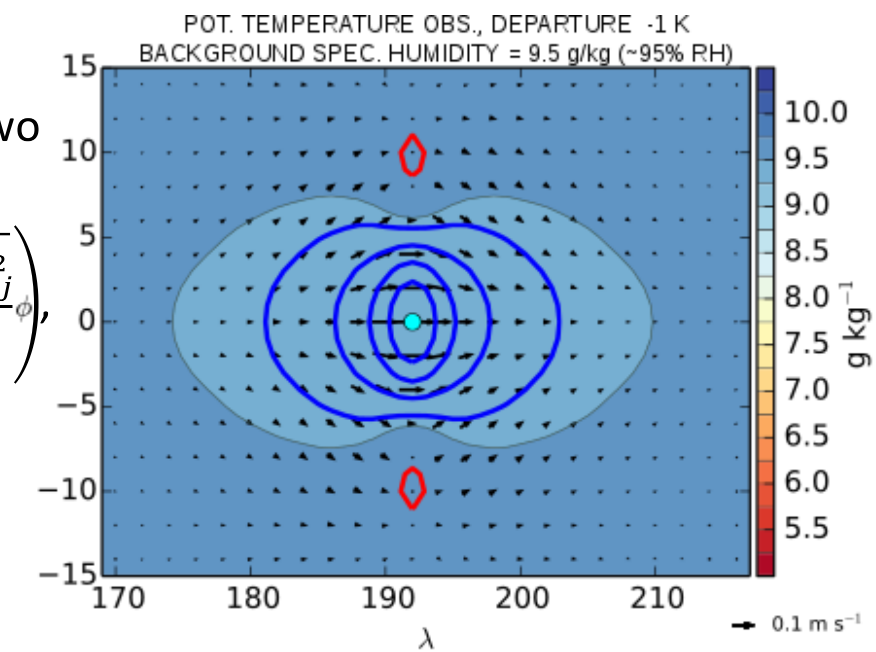
$$\delta \mathrm{RH} = -\frac{L_c}{R_v}\frac{\mathrm{RH}_g}{T_g^2}\gamma\delta\theta + \frac{1}{q_s(T_g)}\delta q \quad \text{and} \quad \delta \mathrm{RH}_n = \frac{\delta \mathrm{RH}}{\sigma(\mathrm{RH}_b + \delta \mathrm{RH}/2)}$$

- Spectral autocorrelation model with anisotropic SOAR corr. function between two distinct point $i$ and $j$ defined as:

$$\rho_{ij} = \left(1 + 2\sqrt{\frac{\Delta x_{ij}^2}{L_x^2} + \frac{\Delta y_{ij}^2}{L_y^2}}\right)\exp\left(-2\sqrt{\frac{\Delta x_{ij}^2}{L_x^2} + \frac{\Delta y_{ij}^2}{L_y^2}}\right),$$

$L_x = 400$ km, $L_y = 200$ km

as zonal flow dominates



# Assimilation model (MADDAM)

**Background-error covariance model for aerosols:**

- Univariate assimilation
- Autocorrelation model the same as for moisture
- Control variable total aerosol mass mixing ratio

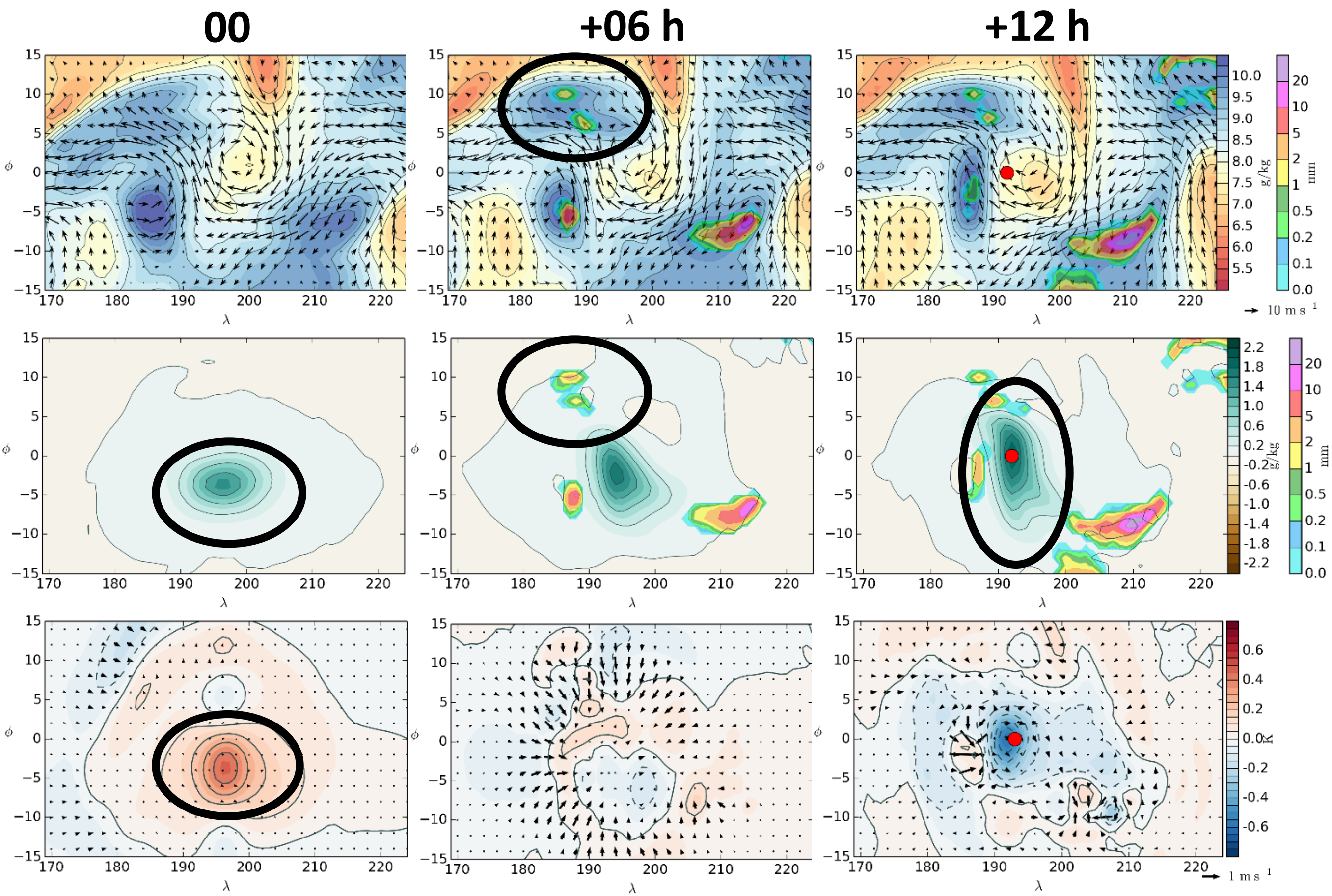
## Setup of assimilation experiments

- 12- or 24-hour 4D-Var
- Max. 10 outer loops, max. 20 inner loops
- Observations generated from nature run and are Gaussianly perturbed
- Background and observational errors are similar:

| | $u$ [m s$^{-1}$] | $v$ [m s$^{-1}$] | $\theta$ [K] | RH [%] | $c$ [$\mu$g kg$^{-1}$] |
|---|---|---|---|---|---|
| $\sigma_b$ | 3.15 | 2.85 | 1 | 5 - 15 | max(0.2 $\overline{c}$, 1) |
| $\sigma_o$ | 3 | 3 | 1 | 10 | max(0.2 $c$, 1) |

# Single moisture observation

- Single specific humidity observation (**RED DOT**) at the end of 12-hour 4D-Var window: $\Delta q = 2.3 \text{ g kg}^{-1}$




Background specific humidity and 6-hour cumulative precipitation

Specific humidity analysis increment and analysis precipitation

Temperature and wind analysis increments

Zaplotnik, Žagar, Gustafsson (QJRMS, 2018)

# 4D-Var wind tracing: motivation

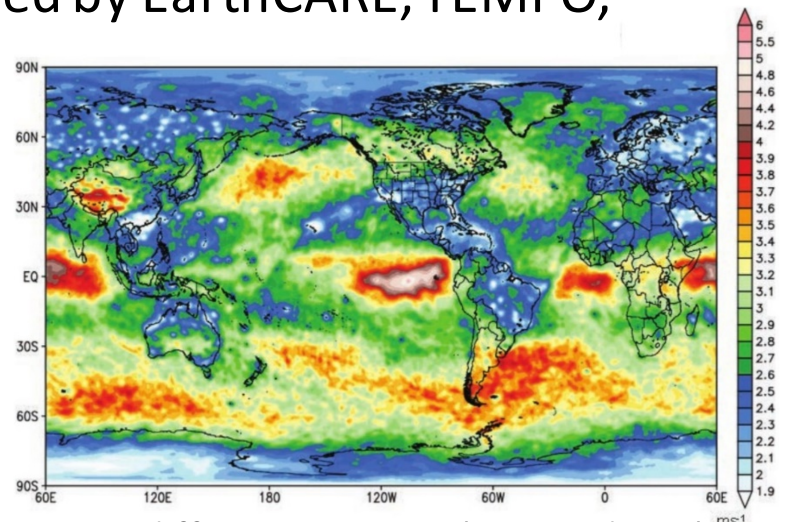
1) An increasing number of atmospheric composition profiles (CALIPSO, Aeolus, Sentinel 5P, followed by EarthCARE, TEMPO, Sentinels 4,5…)

2) NWP has changed lately:

$$\boxed{(\mathbf{v}, p, \rho, T, q)}$$

$$\downarrow$$

Fully-coupled Earth-System prediction system




RMSE differences in 300 hPa wind analyses ECMWF vs GFS (Baker et al., 2014)

3) Need for better wind information in analyses

4) Atmospheric composition and winds dynamically interact

# 4D-Var wind tracing: motivation

1) An increasing number of atmospheric composition profiles (CALIPSO, Aeolus, Sentin… Sentinels 4,5…)

…te…

Can time series of aerosol observations improve wind analyses by using 4D-Var, similarly as the humidity observations do it?

…sys… prediction system

**In theory, yes, however:**

- nonlinear dynamics near saturation,
- sources, sinks,
- errors in the description of aerosol physical processes,
- observation availability,
- very under-determined aerosol analysis etc.

3) Need for better wind information in analyses

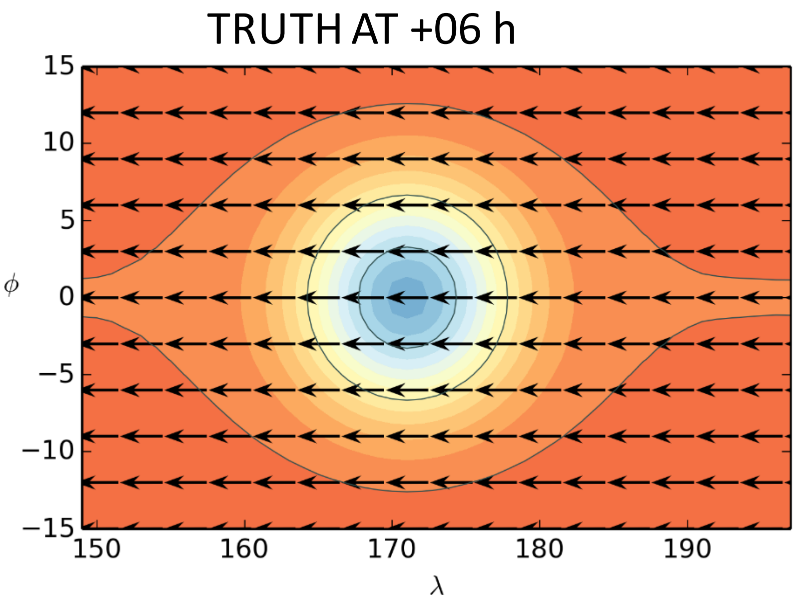
4) Atmospheric composition and winds dynamically interact

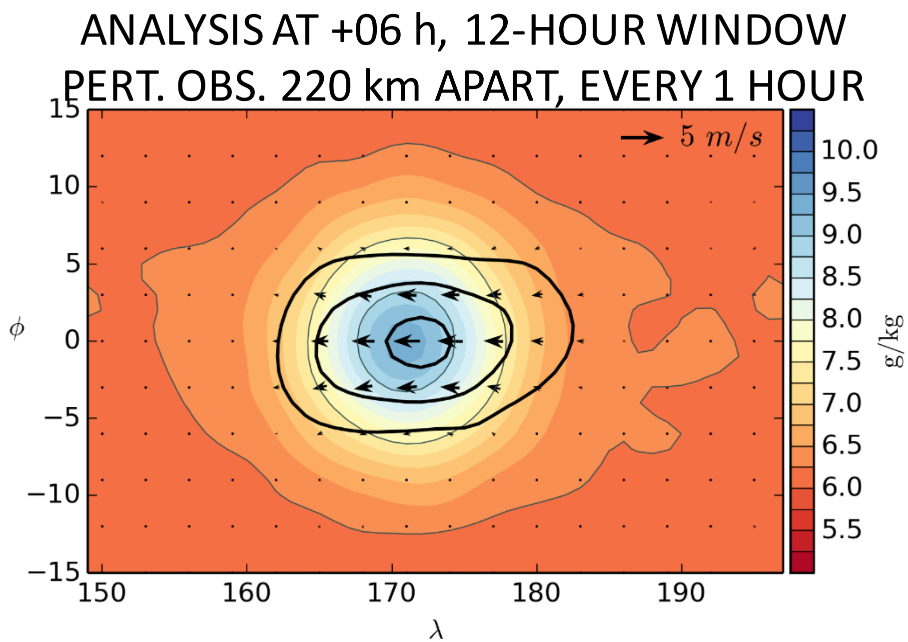
# Previous studies on wind tracing

| APPROACH | AUTHORS | OUTCOME |
|---|---|---|
| Simple 1D and 2D transport models + EKF | Daley (1995, 1996) | First theoretical study of wind tracing. Possible for sufficient variability, high resolution, accurate tracer obs. |
| Operational 4D-Var + humidity obs. | Andersson et al. (1994),<br>Bormann and Thépaut (2004), Geer et al. (2008),<br>Bonavita and Holm (2016) | Significant wind information retrieved |
| Idealized & NWP models + simulated perfect obs. of passive tracers | Peuch (2000), Allen (2013, 2014, 2016) | Positive impact on analysis.<br>Analytical 4D-Var solution for tracing<br>(does not take into account accuracy of retrieved tracer spatial gradients) |
| NWP 4D-Var + ozone obs. | Semane (2009) | Less significant but still positive impact<br>Problem: insufficient availability, accuracy of obs. |
| Operational 4D-Var + trace gases obs. / aerosol obs. | Benedetti et al. (2009)<br>Han and McNally (2010) | Impact of tracer data on wind sensitivities turned off in assimilation due to model/observation biases |

Everywhere at every time!
Wealth of data which are
not used to full potential!

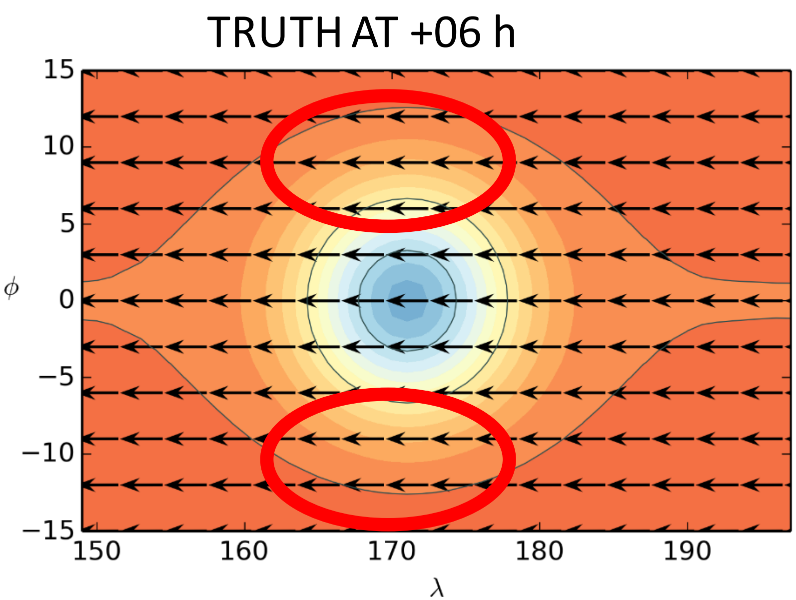
# Wind tracing – linear case

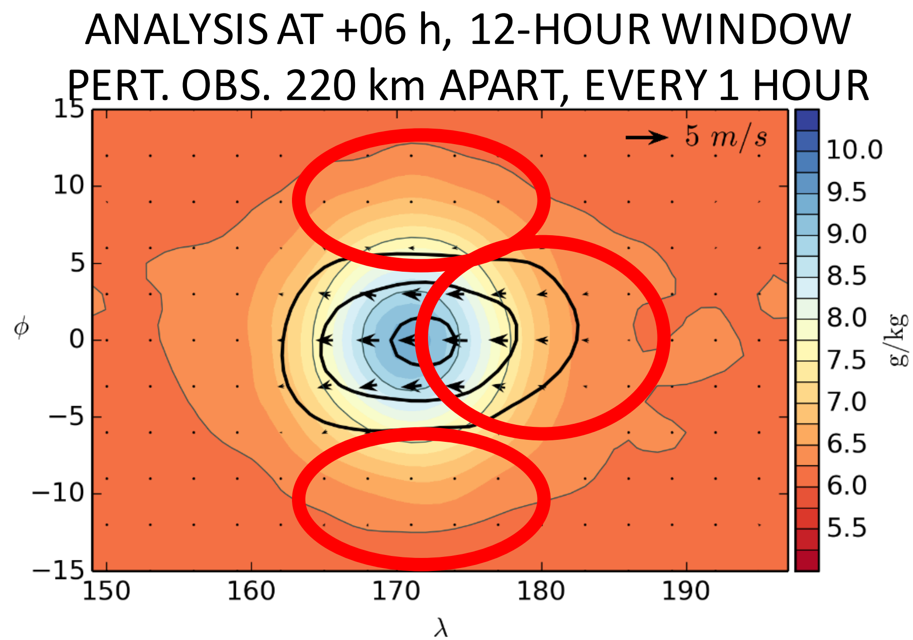



Zaplotnik et al. (QJRMS, 2018)

# Wind tracing – linear case



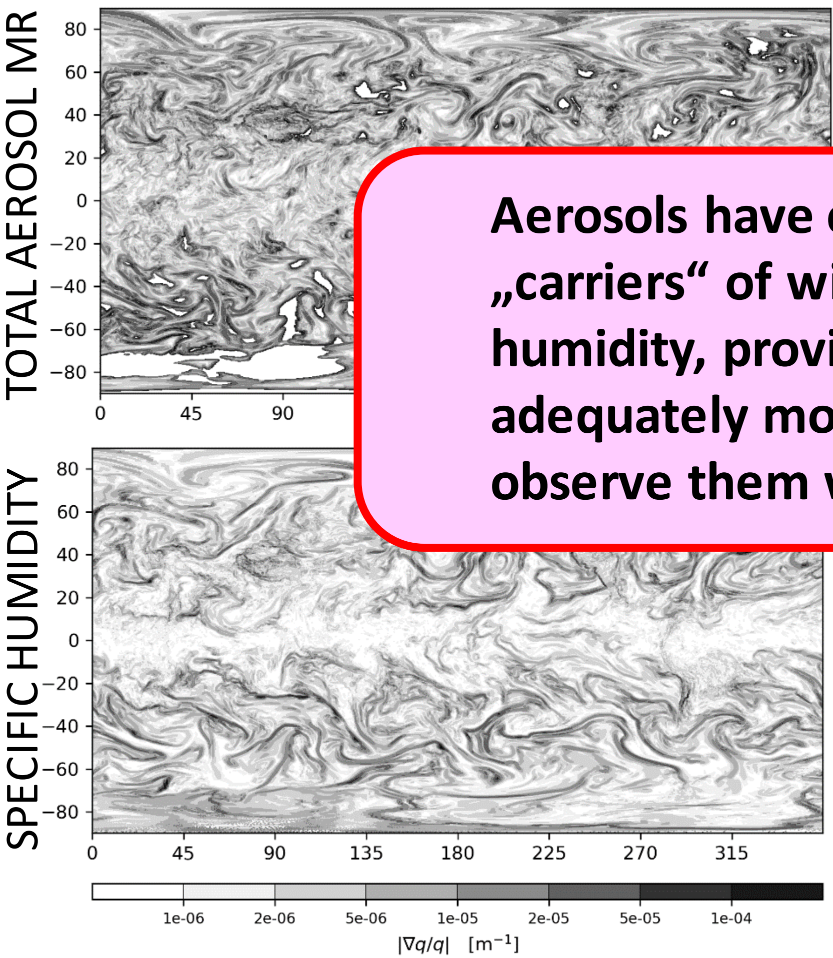

**Basic properties of wind tracing:**

1) $|\delta \mathbf{v}| \propto \left| q_{obs} - q_g \right|$
2) $|\delta \mathbf{v}| \propto \left| \nabla q_g \right| \leftarrow$ determined by humidity observations
3) $\mathbf{v} \cdot \nabla q \neq 0$, else no wind is retrieved
4) Wind better extracted upwind of the perturbation, where the BKGE covariances are stretched, as the flow accelerates $(\partial u / \partial x > 0)$

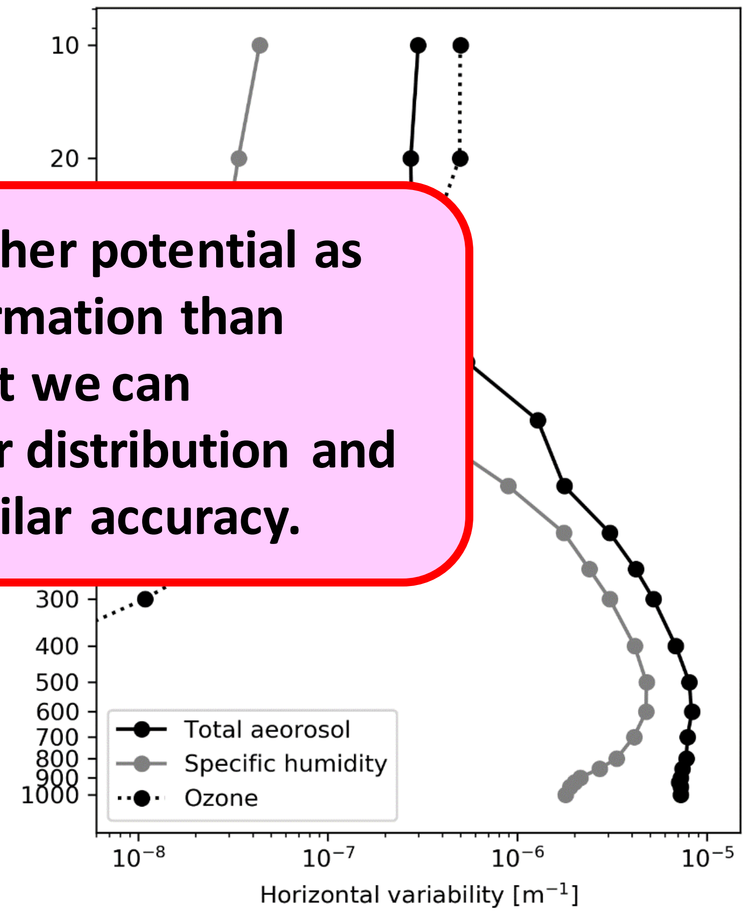
# Further motivation

- Aerosols have higher relative spatial gradients $\left|\frac{\nabla c}{c}\right|$ than humidity (data from CAMS)

700 hPa, single time instance




**Aerosols have even higher potential as „carriers“ of wind information than humidity, provided that we can adequately model their distribution and observe them with similar accuracy.**




Horizontal axis is logarithmic!!

# Ensemble experiments: setup

- Fraternal twin OSSE: truth at 0.25° resolution, assimilation at 1°
- 20 ensemble members

- The initial and boundary conditions provided by operational model and then perturbed using the Randomisation method (Andersson, 2000):
  - Potential temperature at 400 hPa
  - Winds at 700 hPa
  - Specific humidity at 700 hPa
  - Total aerosol mass mixing ratio at 700 hPa from CAMS

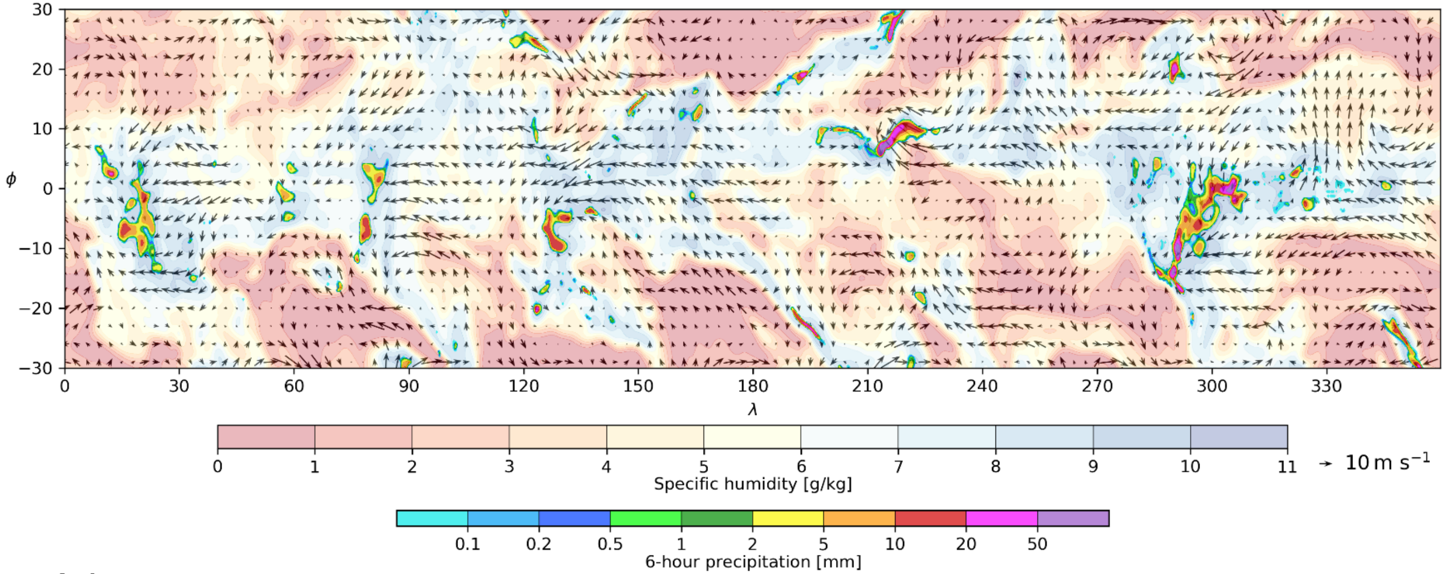
- Analysis quality measured by

$$\text{NRMSE} = \text{RMSE(analysis)}/\text{RMSE(background)}$$

# Ensemble experiments: setup

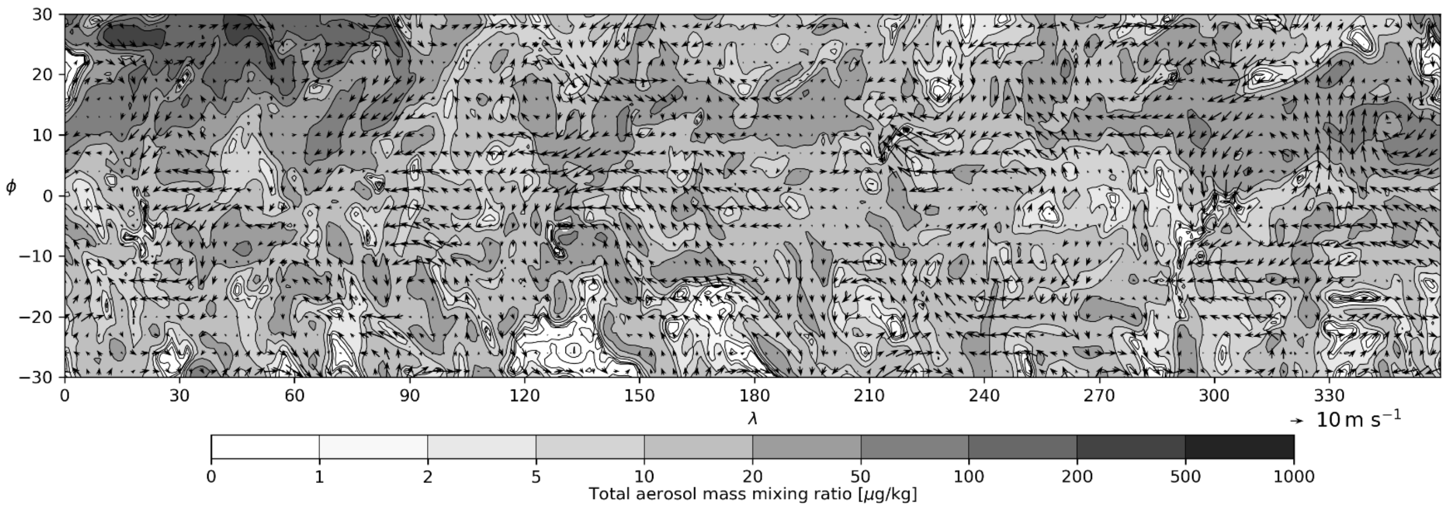
Specific humidity and 6-hour cum. prec.

a)




Total aerosol mass mixing ratio

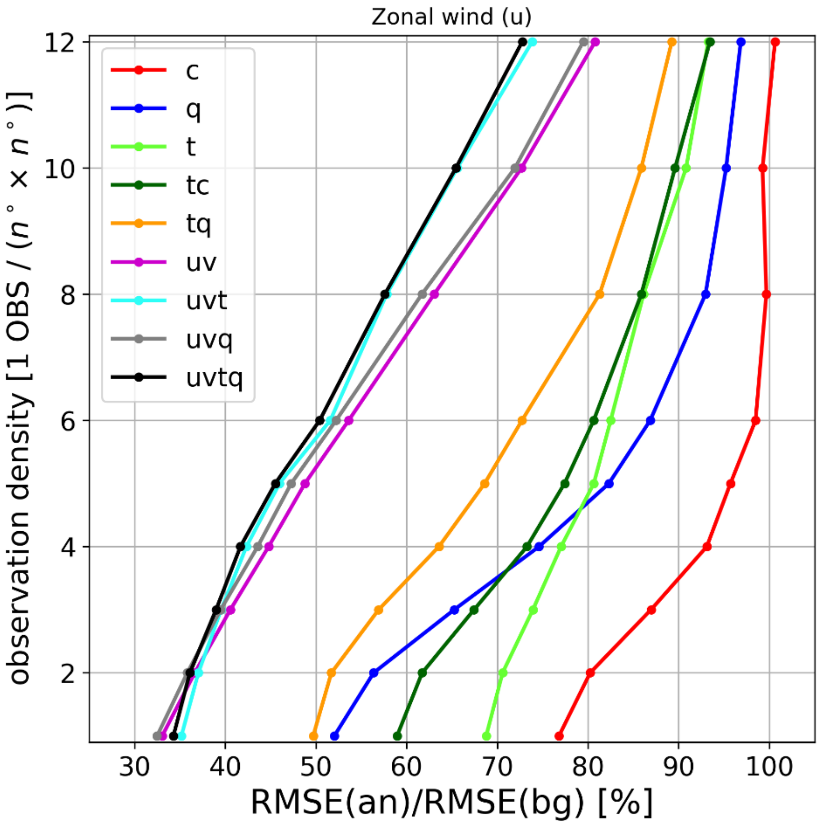
b)



# Impact of the tracer obs. density

Update interval 1 hour

LOWER DENSITY




HIGHER DENSITY

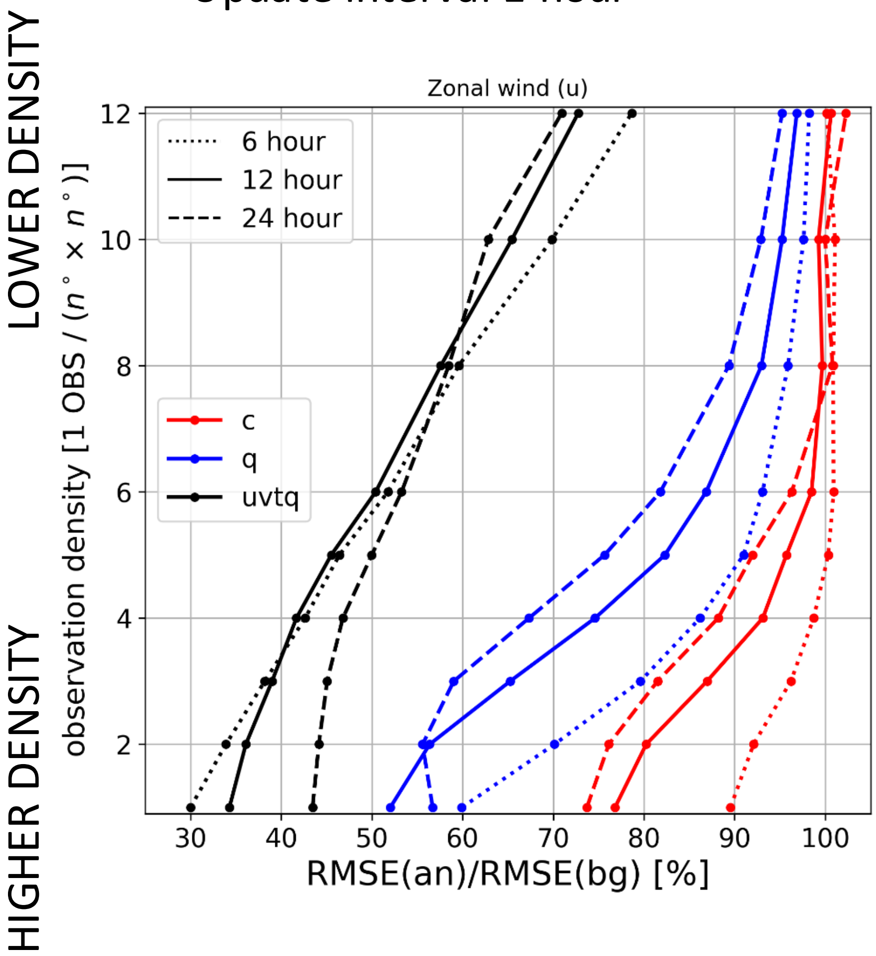
1) More wind extracted from **humidity** obs. than **aerosol** obs. Why?

2) Combined **temperature and humidity** observation (**tq**) reduce the wind error by roughly 45-50%, **wind** observations (**uv**) reduce the wind error by 60-65%

Zaplotnik, Žagar, Benedetti, Semane (to be submitted to QJRMS, 2019)

# Impact of the assim. win. length

Update interval 1 hour




- Wind tracing is better for longer (24-hour) window as the observed tracer distribution changes more
- Information on one observation is spreaded further and is more flow-dependent
- The observed fields are analysed worse for longer windows:
  - model error
  - NRMSE is for longer windows smaller towards the middle of ass. win.

Zaplotnik, Žagar, Benedetti, Semane (to be submitted to QJRMS, 2019)

# Flow-dependent wind tracing

- **Problem:** feedback of the tracers on wind is switched-off in the TL and AD models in the operational NWP due to model/observational biases. This always deteriorates the tracer analysis [not shown] and neglects the useful wind information in many regions!
- **Idea:** to make better use of existing tracer observations by selectively switching the feedback ON or OFF!
- Locally and temporally manipulate the adjoint and TL models (using function $\theta(x,y,t)$)

$$-\frac{\partial \delta u^*}{\partial t} = +u\frac{\partial \delta u^*}{\partial x} - \delta u^*\frac{\partial u}{\partial x} - \boxed{\theta(x,y,t)}\left(\delta c^*\frac{\partial c}{\partial x} + c\frac{\partial \delta c^*}{\partial x}\right)$$

$$\frac{\partial \delta c}{\partial t} + \boxed{\theta(x,y,t)}\left(\delta u\frac{\partial c}{\partial x} + c\frac{\partial \delta u}{\partial x}\right) + u\frac{\partial \delta c}{\partial x} + \delta c\frac{\partial u}{\partial x} = 0,$$

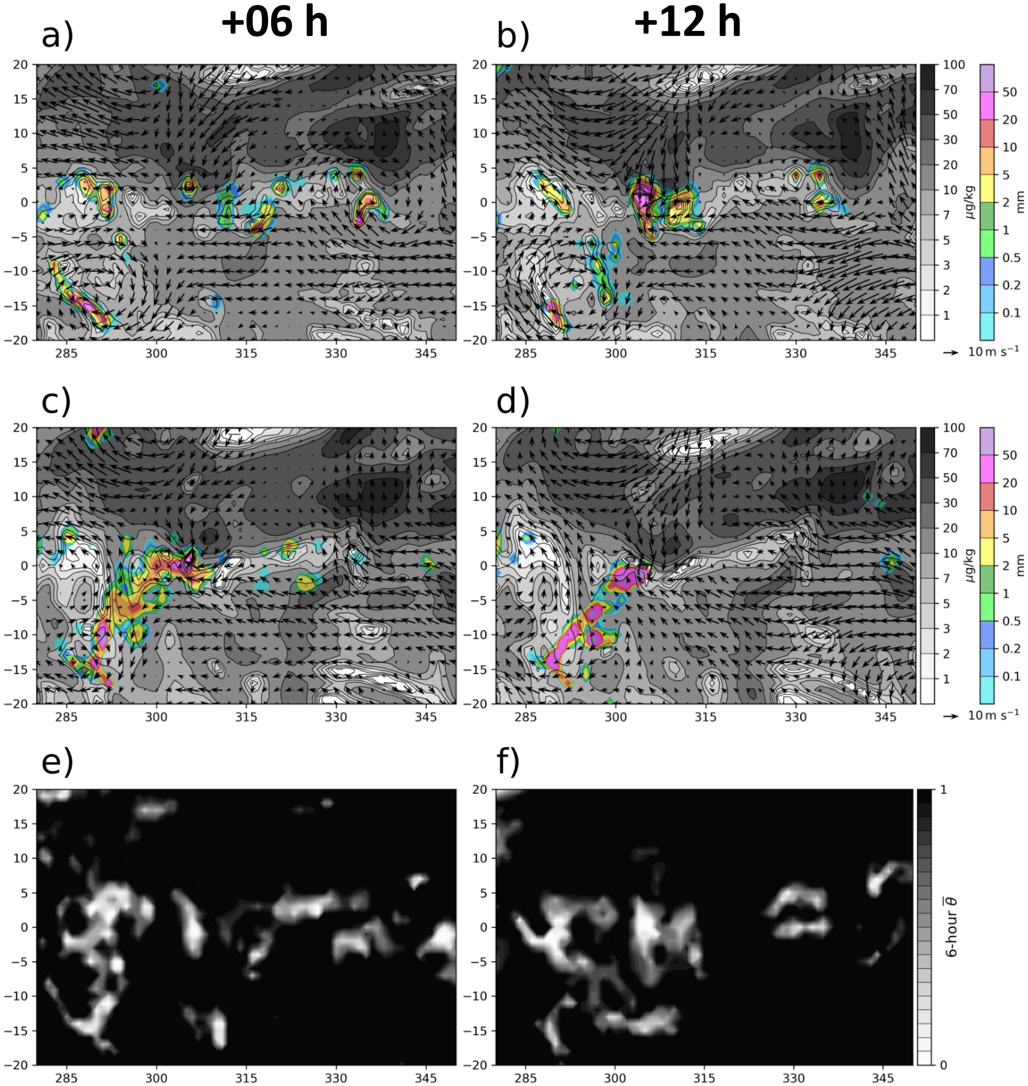
OBJECTIVE CRITERION:

$$E_{unc} = \frac{1}{N}\sum_{i=1}^{N}\left|\left(\frac{\partial c}{\partial t}\right)^i_{phys} - \left\langle\frac{\partial c}{\partial t}\right\rangle_{phys}\right|$$

$$\theta = \begin{cases} 0, & E_{unc} > \frac{1}{5}\left|\left\langle\frac{\partial c}{\partial t}\right\rangle_{adv}\right| \\ 1, & \text{otherwise.} \end{cases}$$

Zaplotnik, Žagar, Semane (to be submitted to QJRMS, 2019)

# Flow-dependent wind tracing




BACKGROUND

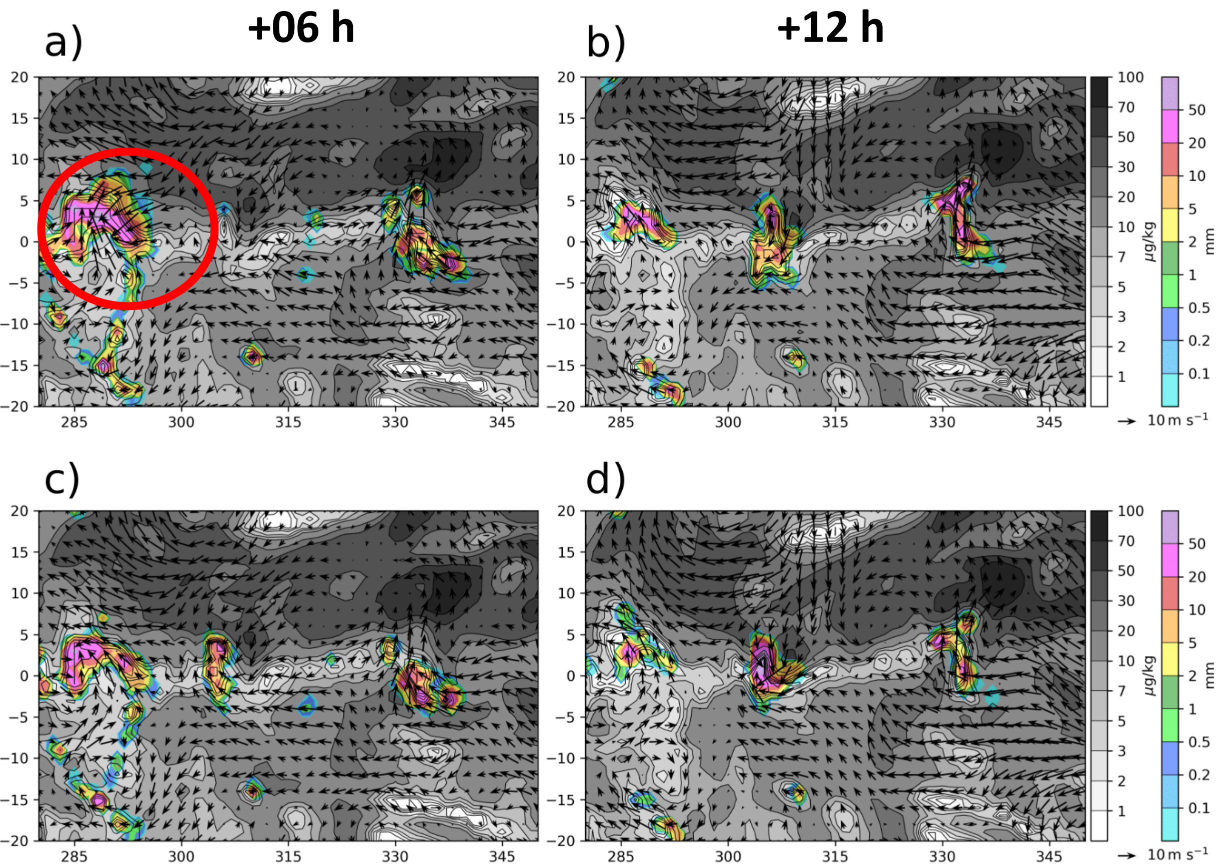
NATURE RUN

- Background perturbed by randomisation method (50 ens.)
- Wet deposition parameter perturbed (proxy for model error)
- $\theta = 1$ (tracer-wind feedback ON, if physical forcing uncertainty lower than 1/5 of the mean advection rate)

6-hour mean $\theta$

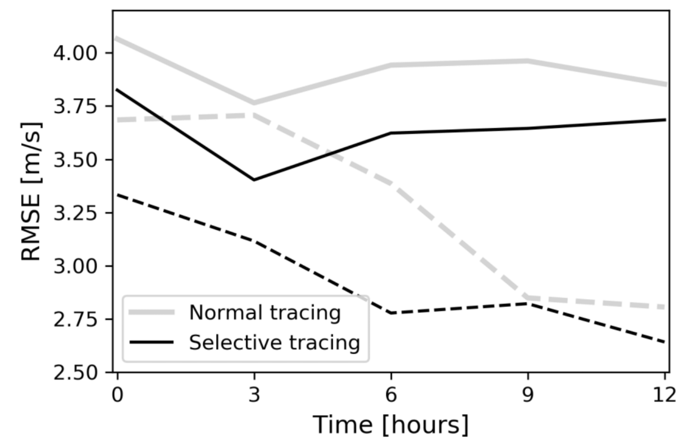
Zaplotnik, Žagar, Semane (to be submitted to QJRMS, 2019)

# Flow-dependent wind tracing




NORMAL ASSIMILATION (TRACER-WIND FEEDBACK SWITCHED ON EVERYWHERE)

FLOW-DEPENDENT (SELECTIVE) 4D-VAR WIND TRACING

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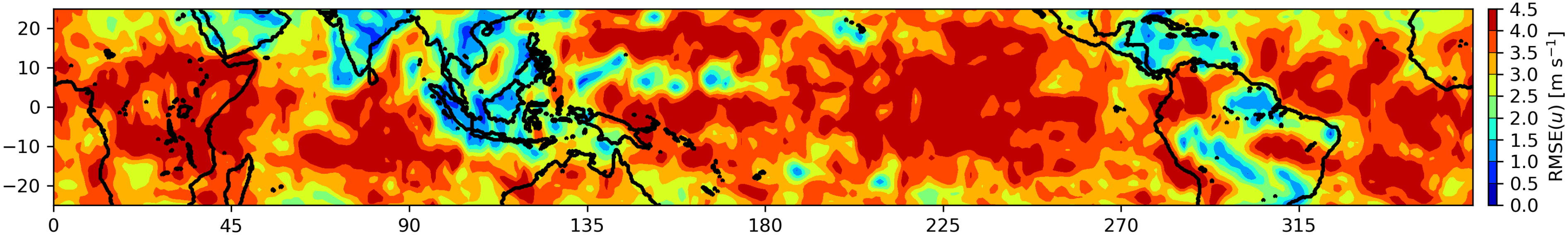
# Conclusions

- The MADDAM system has been applied to study 4D-Var wind tracing
- Statistics from ensemble of imperfect model OSSEs:
    - Dense aerosol data alone reduce the analysis wind RMSE by 15-20%, humidity 35-45%, combined temperature-humidity by 45-50%, direct wind observations by 60-65%
    - Longer windows more beneficial, spatial density more important than temporal
    - Significant potential for tracing from aerosol data in dry areas with high advection rate, e.g. tropical and subtropical Atlantic
- **NEW IDEA: Flow-dependent wind tracing shown to improve wind analyses!**

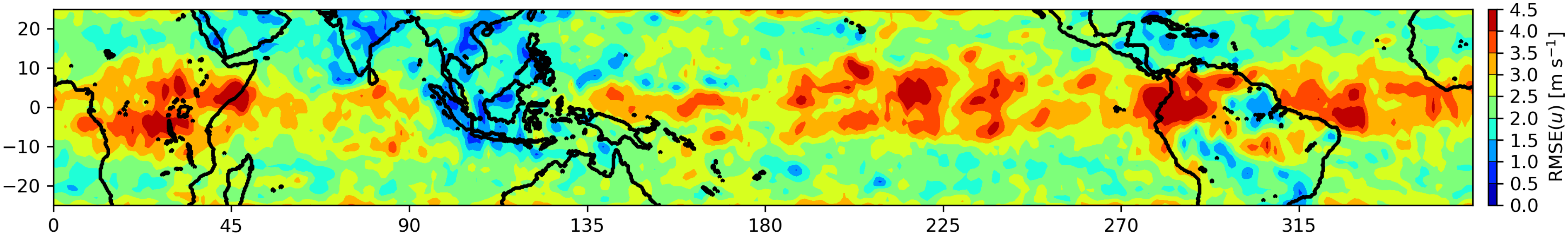
- MADDAM is envisaged to serve as a testbed for new developments in 4D-Var assimilation and a numerical lab for studying the role of inertio-gravity waves and their interaction with humidity across many scales
- Future work: improving the background-error modelling of spatially highly variable fields, e.g. aerosols!
- Intermediate-complexity assimilation systems needed to bridge the gap between assimilation systems with 1D models and NWP!

# Zonal wind analysis error for different obsevation types

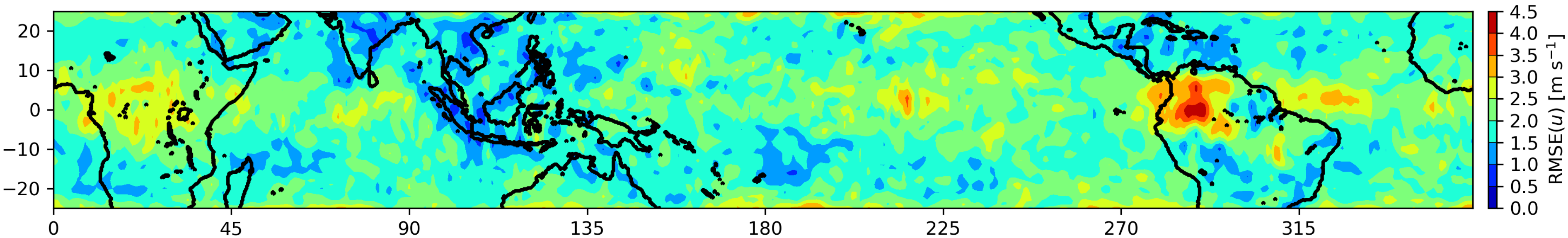
**uv** from radiosondes (real network used)




**uv** from radiosondes + dense **T** observations (slow mass-wind adjustment in Tropics)



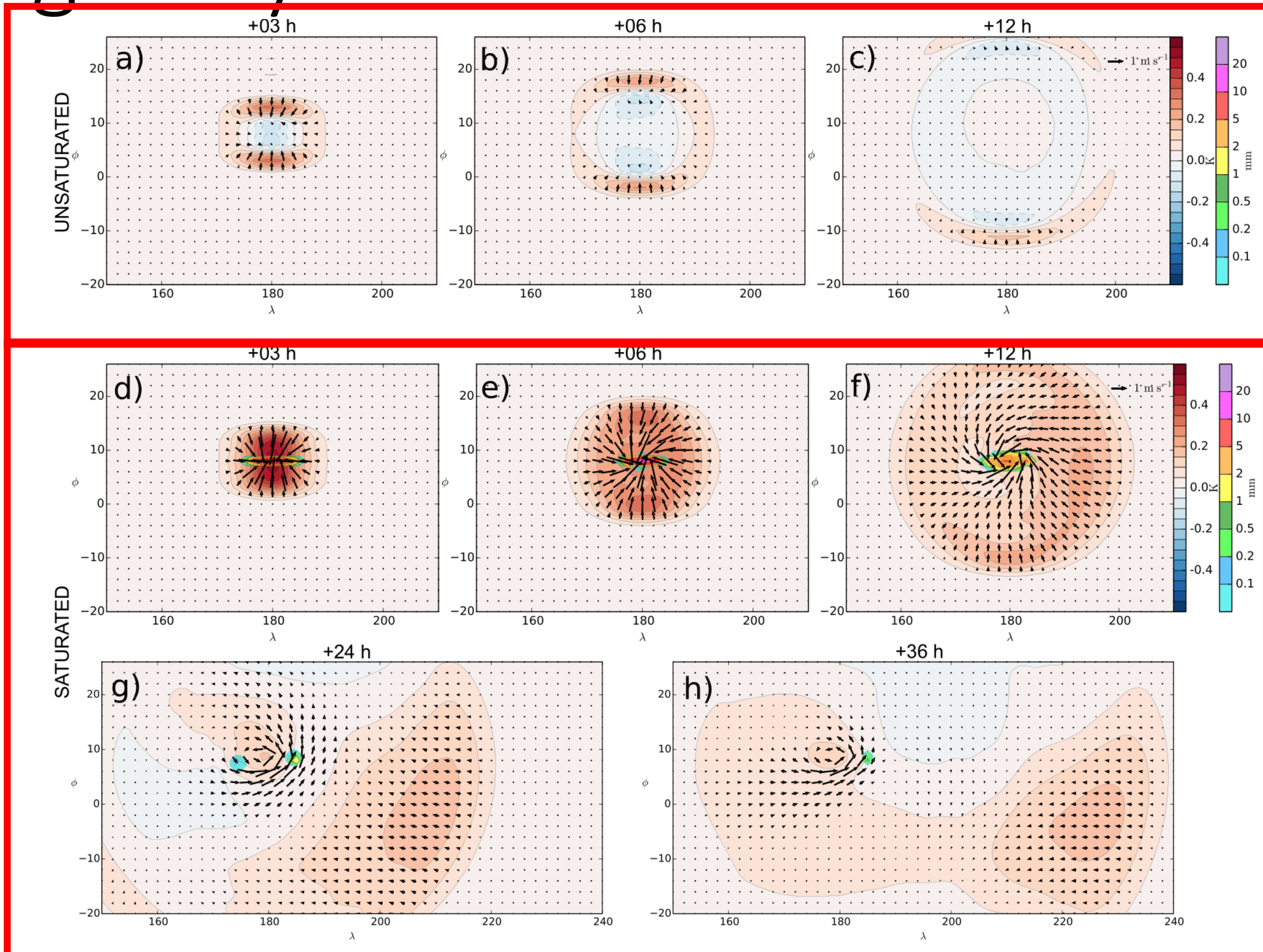

**uv** from radiosondes + dense **T,q** observations (reduced zonal wind error close to equator)



# Thank you!

# Inertio-gravity waves and 4D-Var

**Adjustment** to 1 K temperature pert.

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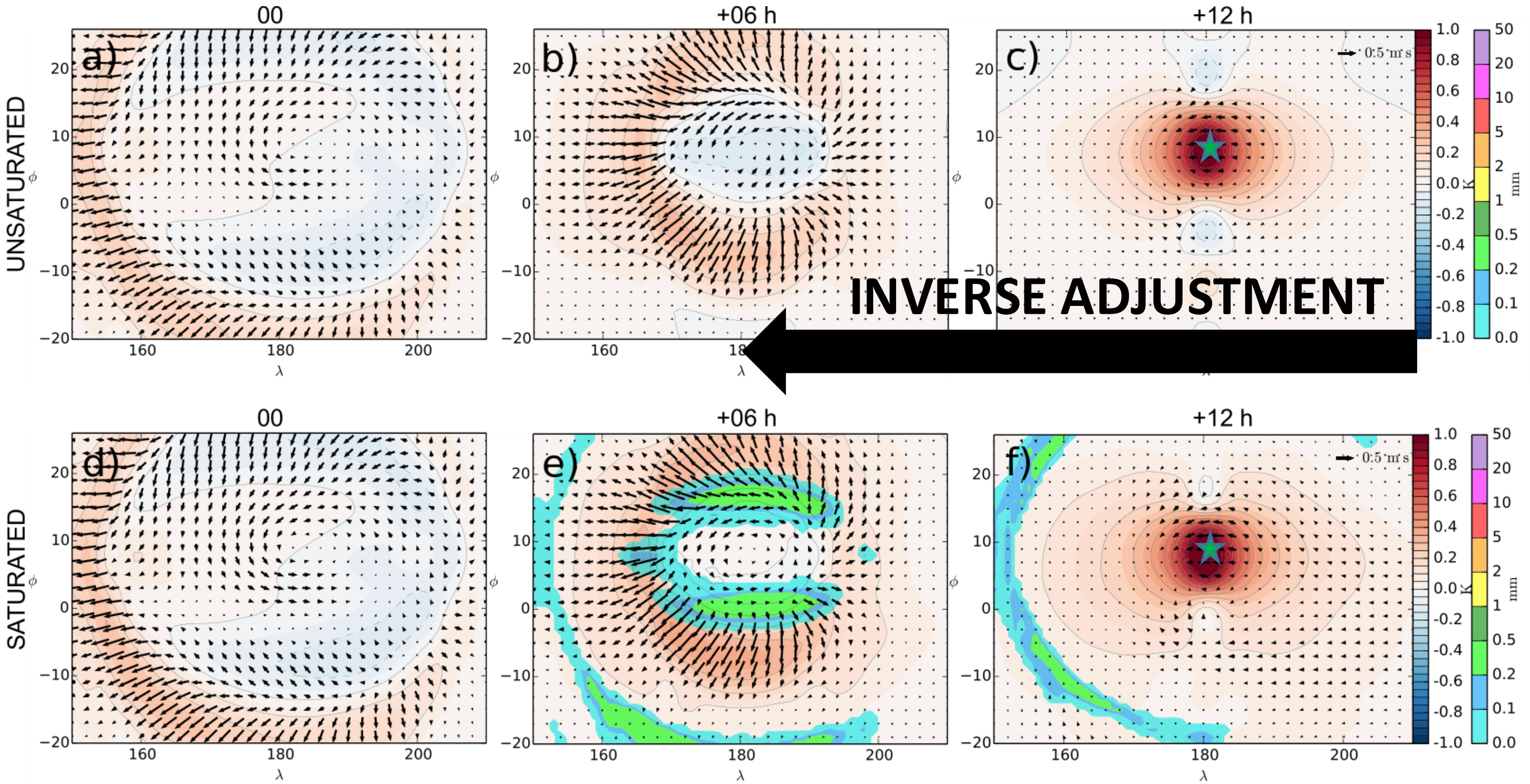
# Inertio-gravity waves and 4D-Var

- **Assimilation** of temperature perturbation with deperature + 2K at the end of 12-hour time window

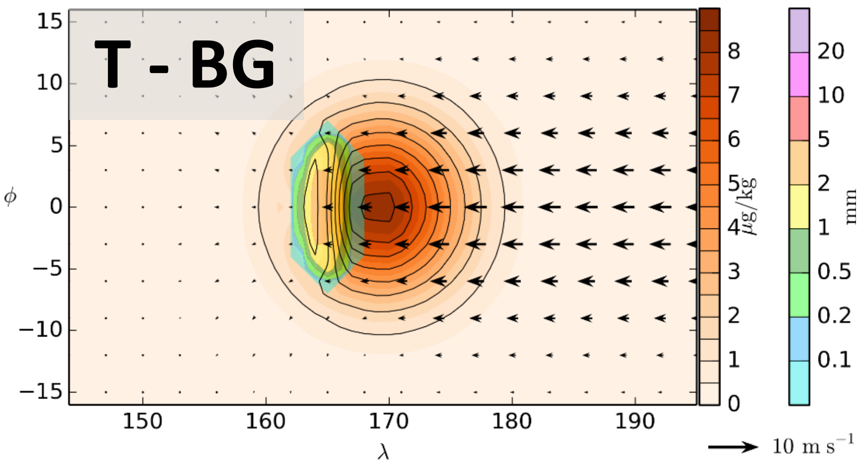


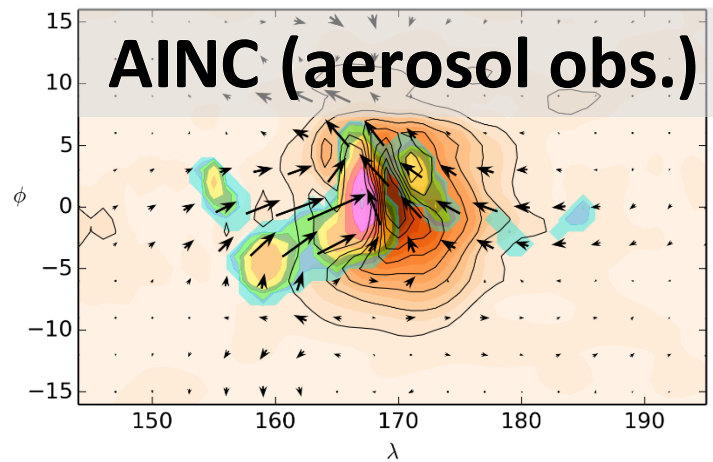

Zaplotnik, Žagar, Gustafsson (QJRMS, 2018)

# Wind tracing from aerosol obs. in saturated atmosphere

**Aerosol, moisture, wind couplings:**
- Advection
- Condensation heating
- Wet deposition by precipitation

Despite such simple coupling, 4D-Var can barely resolve the processes due to positive feedback loop occurring




**Aerosols and humidity strongly differ as tracers!**
**Main sink of humidity** is directly coupled with winds (and temperature).
**Main sink of aerosols** is directly coupled to humidity fields (precipitation)

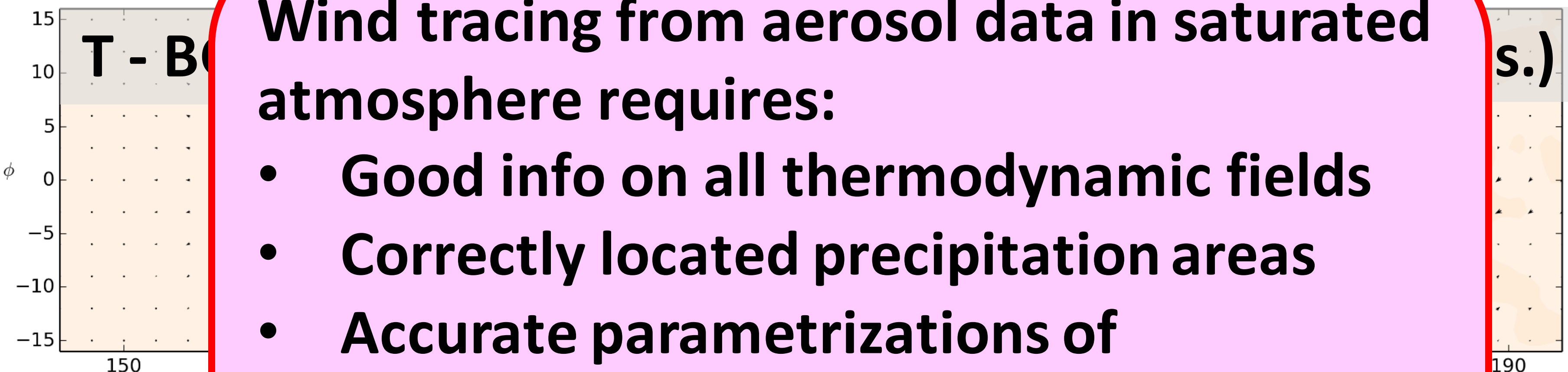
**Analysis running into a positive fdb. loop:**
1) The aerosol conc. is lowered by strong westerly advection
2) This leads to convergence and strong precipitation and deposition, which additional lowers the aerosol conc.
3) This results in even more convergent flow in next outer loop. → 2)

# Wind tracing from aerosol in saturated atmosphere

**Aerosol, moisture, wind couplings:**

- Advection
- Condensation heating
- Wet depo…

Despite such simple coupling, 4D-Var can barely resolve the processes due to positive …ring




**Wind tracing from aerosol data in saturated atmosphere requires:**

- **Good info on all thermodynamic fields**
- **Correctly located precipitation areas**
- **Accurate parametrizations of sink/source processes**
- **Dense and accurate observations**